

Constraints on the Number Density of Evaporating Primordial Black Holes for the Chromospheric Evaporation Models

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Cosmic gamma-ray bursts with primary-photon energies ≥ 10 GeV are sought in the data from the Andrych array obtained in the mode of detection of a single cosmic-ray component during a net observation period of 2005.4 d. The distribution of fluctuations of the detector counting rate agrees with the expected cosmic-ray background, the only exception being an event with a deviation of 7.9σ . Constraints on the number density of evaporating primordial black holes in a local region of the Galaxy are obtained for the chromospheric evaporation models.

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INTRODUCTION

Primordial black holes (PBHs) can be formed in the early Universe due to the gravitational collapse of primordial cosmological density fluctuations. Theoretical predictions of the probability of PBH formation are strongly dependent on the accepted theory of gravitation and the model of gravitational collapse. The process of black-hole evaporation, which is used to seek them experimentally, is also far from being completely understood. Thus, PBH detection will provide important information on the early Universe and can be a unique test of the general theory of relativity, cosmology, and quantum gravity [1]. Knowledge of the PBH spatial distribution is important for their direct search. The number density of PBHs in our Galaxy can be many orders of magnitude higher than the average number density of PBHs in the Universe [2], so that the constraints based on the results of direct searches can be much more stringent than those implied by measuring the diffuse extra-Galactic γ -ray background.

The bursts of high-energy γ rays are generated at the final stages of PBH evaporation. Since the calculated temporal and energy characteristics of such bursts depend on the accepted theoretical evaporation model [3], the experimental technique used to detect PBH emission and, correspondingly, the resulting constraints on the number density of PBHs in the local Universe are strongly model dependent. In the model without a chromosphere [4], the evaporating particles do not interact, all quarks propagate freely, and evaporating particles fragment independently of each other. The photon spectrum is formed by the quark fragmentation and decay of unstable hadrons; hence, this spectrum is not

thermal. According to the DK02 [5] and H97 [6] chromospheric models, the interacting evaporated particles form a quasi-chromosphere, which results in the strong energy fragmentation and, accordingly, in the steep photon spectrum at high energies. The spectra of γ rays emitted by PBHs depend on the time until the end of the black-hole evaporation. The evaporation models were analyzed in more detail in [3]. The time interval until the end of black-hole evaporation during which 99% of the γ -ray photons with energies $E_\gamma \geq E_{th}$ are emitted is called the burst duration for the threshold E_{th} . The burst duration as a function of the threshold energy is

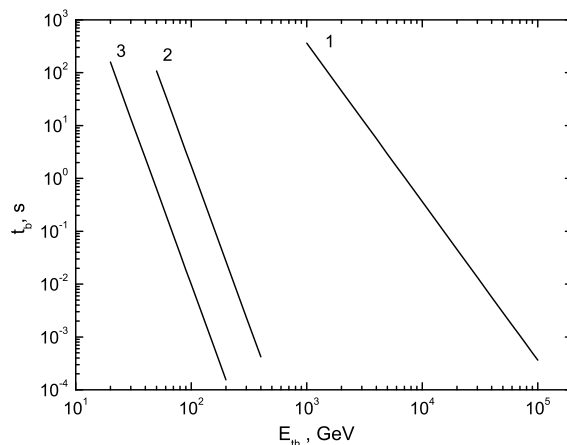


Fig.1. Burst duration versus the threshold energy of gamma-ray photons for various evaporation models: (1) the model without a chromosphere [4], (2) the DK02 model with a chromosphere [5], and (3) the H97 model with a chromosphere [6].

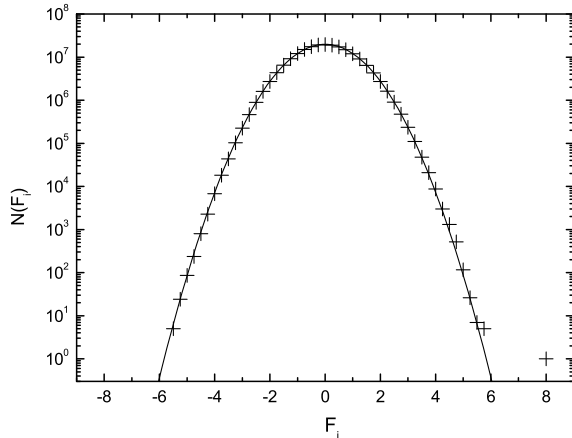


Fig. 2. Distribution in the parameter F_i for the data gathered during nine years; the Gaussian fit is shown by the solid line.

plotted in Fig.1 for three evaporation models. Until recently, the bursts of high-energy γ rays from the final stage of PBH evaporation were sought using several arrays for detecting the extensive air showers (EASs) from cosmic rays [7] and the Whipple Cherenkov telescope [8]. Since the threshold energy of the primary γ -ray photons is high and the duration of the high-energy γ -ray burst predicted by the chromospheric models is too short (much less than the dead time of these arrays), the results of these experiments can be interpreted only within the framework of the evaporation model without a chromosphere.

Within the framework of the chromospheric models, the PBH events can be sought directly by the method of detecting spikes in the total counting rate of the arrays operating in the regime of the detection of a single cosmic-ray component. The particle arrival direction in this regime is not determined, while the effective energy of the primary gamma-ray photons depends mainly on the altitude of the array above sea level. Such a technique was employed earlier to seek cosmic gamma-ray bursts with energies exceeding a few GeVs [9, 10, 11].

EXPERIMENT

The Andyrchy EAS array of the Baksan Neutrino Observatory (Institute for Nuclear Research, Russian Academy of Sciences) is located at an altitude of 2060m above sea level and consists of 37 scintillation detectors. The area of each detector is 1 m^2 . To detect a single cosmic-ray component, the total counting rate of all of the detectors is measured each second. The search for

γ -ray bursts using this technique is carried out against the high cosmic-ray background ($\bar{\omega} = 11440 \text{ s}^{-1}$), which requires the highly stable and reliable performance of all equipment. The monitoring is realized through simultaneous measurements (with 1-s acquisition rate) of the counting rates in the four parts of the array comprising 10, 9, 9, and 9 detectors, respectively. A detailed description of the array and its operating parameters is given in [12]. The probabilities $P(E_\gamma, \theta)$ of the detection of the secondary particles that are created by the primary γ -ray photons with energy E_γ and that incident onto the array at the zenith angle θ in a hypothetical infinite-area Andyrchy detector were obtained by simulating the electromagnetic cascades in the atmosphere and detector [11]. Since the probability of the detection of a γ -ray photon is a fairly smooth function of the photon energy, the median energy of the primary γ -ray photons detected by the detector depends on their energy spectrum. In the case of a source with zero zenith angle having a power-law spectrum with an exponent of -2.0 , the median energy of the primary γ -ray photons is equal to 10 GeV.

Deviations in the array counting rate lasting $\Delta t \leq 1\text{s}$ are sought using the parameter F_i that is equal to the deviation (measured in units of the Poisson sigma) of the number of counts k_i during the i th second of a 15-min interval from the average number of counts \bar{k} during this interval: $F_i = (k_i - \bar{k})/\sqrt{\bar{k}}$. Since variations in the cosmic-ray intensity over a time of 15 min are negligible in the first approximation and the average counting rate is fairly high, one can expect that the parameter F_i has a Gaussian distribution with the zero mean value $V = 0$ and unit standard deviation $\sigma = 1.0$. The parameter D_i is used to characterize the differences in the counting rates of the array parts: $D_i = \frac{1}{4} \sum_{j=1}^4 (F_i^j - \bar{F}_i)^2$. Here, F_i^j is the deviation of the j th part of the array and \bar{F}_i is the average of the four values for the i th second of a 15-min interval. Further processing was done only for the 1-s points for which the condition $D_i \leq D_{\text{bound}}(F_i)$ was valid. The values $D_{\text{bound}}(F_i)$ were obtained by the Monte Carlo method under the assumption that k_i has a Poisson distribution. This condition makes it possible to reject points for which the differences in the counting rates of the array parts are unreasonably large, i.e., eliminate the instrumental error. The useful events (1-s points) can be rejected with a probability of 2×10^{-9} for all of the events and with a probability of 1.3×10^{-3} for events with $F_i \geq 5$. About 0.01% of events were rejected from the entire volume of the experimental data according to this criterion.

Figure 2 shows the experimental distribution in the parameter F_i plotted using the data gathered during

nine years (2005.4 d of the net observation time). The experimental data up to $\sim 6\sigma$ are fitted well by a Gaussian distribution with the mean value $V = -(0.0025 \pm 0.0004)$ and standard deviation $\sigma = 1.006$. The only event with a large (7.9σ) deviation was detected April 17, 2002 at 17:31:29 UT. No γ -ray bursts were detected at this time by space-borne instruments.

EXPECTED SIGNAL FROM PBHS

Let a PBH be located at distance r from the array and observed by this array in the direction specified by the zenith angle θ . Then, the mean number of γ -ray photons detected by the array is equal to

$$\bar{n}(\theta, r) = \frac{S(\theta)}{4\pi r^2} N(\Delta t, \theta), \quad (1)$$

where $N(\Delta t, \theta)$ is the total number of the gamma-ray photons emitted by the PBH that can be detected by the array:

$$N(\Delta t, \theta) = \int_0^\infty dE_\gamma P(E_\gamma, \theta) \frac{dN_\gamma}{dE_\gamma}(\Delta t). \quad (2)$$

Here, $(dN_\gamma/dE_\gamma)(\Delta t)$ is the spectrum of gamma-ray photons emitted by the PBH during the time interval Δt until the end of the PBH evaporation and $S(\theta)$ is the area of the array. The number of bursts detected during the entire observation time T can be written as

$$N = \rho_{\text{pbh}} T V_{\text{eff}}, \quad (3)$$

where

$$V_{\text{eff}} = \int d\Omega \int_0^\infty dr r^2 F(n, \bar{n}(\theta, r)) \quad (4)$$

is the effective volume of the space surveyed by the array, ρ_{pbh} is the number density of the evaporating PBHs, and $F(n, \bar{n}) = e^{-\bar{n}} \bar{n}^n / n!$ is the Poisson probability of the detection of n events for the mean value \bar{n} .

CONSTRAINTS ON THE PBH NUMBER DENSITY FOR THE CHROMOSPHERIC MODELS

The upper limit for the PBH number density (excluding the single spike in the counting rate) can be obtained from the absence of events with deviations $\geq 6\sigma$ for $\Delta t = 1\text{s}$, i.e., the effective volume of space (4) surveyed by the array is calculated for $n = 6\sigma = 642$. If the evaporating PBHs are uniformly distributed over the local Galactic region, then the upper limit ρ_{lim} for

the number density of evaporating PBHs at the 99% confidence level is calculated by the formula

$$\rho_{\text{lim}} = \frac{4.6}{V_{\text{eff}} T}, \quad (5)$$

where the net observation period is $T = 5.5\text{yr}$. The substitution of the V_{eff} values for each chromospheric evaporation model into Eq. (5) yields a 99%-C.L., with the upper limits 1.8×10^{12} and $1.7 \times 10^{13} \text{ pc}^{-3}\text{yr}^{-1}$ for the DK02 and H97 evaporation models, respectively.

PROBABLE PBH EVENT

Let us assume that the event of 7.9σ deviation is caused by the γ -ray burst from an evaporating PBH. Then, according to the evaporation model [4] without a chromosphere, the average number density of evaporating PBHs is equal to $2.9 \times 10^{12} \text{ pc}^{-3}\text{yr}^{-1}$, which is many orders of magnitude higher than the upper limits obtained earlier in several experiments [7, 8].

According to the chromospheric models, the average number density of PBHs is equal to $\bar{\rho} = 7.8 \times 10^{11}$ and $7.2 \times 10^{12} \text{ pc}^{-3}\text{yr}^{-1}$ for the DK02 and H97 models, respectively. Note that a single spike in the total counting rate was also observed at the EAS-TOP array [9]. The deviation amounted to 20.6σ for $\Delta t = 2\text{s}$. If this spike is a PBH event, then the average number density of evaporating PBHs amounts to $\bar{\rho} = 6.2 \times 10^{12}$ and $3.7 \times 10^{13} \text{ pc}^{-3}\text{yr}^{-1}$ for the DK02 and H97 models, respectively. Despite the significant (more than an order of magnitude) difference between the mean values, the 99% confidence intervals for each model intersect with each other. Thus, if the events with large deviations in the total counting rates of the EAS-TOP and Andyrchy arrays result from γ -ray bursts from evaporating PBHs, then the average number density of the evaporating PBHs is $7.5 \times 10^{10} - 5.2 \times 10^{12}$ and $4.5 \times 10^{11} - 4.8 \times 10^{13} \text{ pc}^{-3}\text{yr}^{-1}$ for the DK02 and H97 models, respectively.

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